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Development of Modelling and Simulation tools for Geothermal Basements and Deep Foundations in Soft Clays

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Gothenburg
December 2016

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DEVELOPMENT OF MODELLING AND SIMULATION TOOLS FOR GEOTHERMAL BASEMENTS AND DEEP FOUNDATIONS IN SOFT CLAYS

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Executive summary

Pile heat exchangers are fast emerging as a potentially viable alternative to the more prevalent borehole heat exchangers for the provision of space heating and cooling. In the last decade or so, the use of geothermal piles has increased sharply in many countries including Belgium, China, Japan, Switzerland, the Netherlands, United Kingdom, and the United States, among others. In Sweden, however, interest in geothermal piles has been surprisingly scant. This is despite the fact that most of the infrastructure and buildings in Sweden are founded on piled foundations.

Early estimates suggest that approximately 75 % of heating requirements and 90 % of cooling requirements of a typical Swedish office building could be provided by geothermal piles. Initial studies also indicate quick payback and large carbon savings. On the other hand, as several Swedish cities are founded in areas with very soft soil conditions with high groundwater tables, there are concerns that pile heat exchangers with cyclic thermal loading could trigger excessive creep deformations. Most of the Swedish research on geothermal piles and cyclic thermal loading dates back to 1980s. Today, both analysis and test methods for understanding soft clay behaviour have improved significantly. Hence, there is a need to revisit the topic of cyclic heating and cooling of Swedish soft clays to fully understand the implications of the use of geothermal piles.

This project, funded by Swedish Energy Agency, has dealt with the development of mathematical models for thermal modelling of geothermal piles in Swedish soft clay conditions. The new models include a method to determine the thermal impact of the building on the underlying pile heat exchangers and calculation methods to evaluate the thermal resistance of the pile heat exchangers. An existing borehole model has also been updated for modelling of irregular configurations of geothermal piles. The mathematical models developed in this project can be implemented in any computer code to be incorporated into the existing building energy simulation software. The models can also be used to develop controllers and control schemes to maximize the performance of pile heat exchangers.

The project has also demonstrated the application of driven steel and precast pile heat exchangers in Swedish soft clays and has established the importance of acquiring in-situ measurements to determine key design parameters. The results from the project have been presented in seven journal and conference proceeding papers, three research reports, and one book chapter.

Keywords: geothermal piles, ground source, pile heat exchanger, design, modelling, simulation, testing, pile thermal resistance, heating, cooling, thermal response test

Utveckling av Modeller och Dimensioneringsverktyg för Djupa Grundläggningar i Lösa Leror

Saqib Javed
Installationsteknik
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Sammanfattning

Användningen av pålar som markvärmeväxlare blir allt vanligare som ett möjligt alternativ till de mer vanligt förekommande borrhålsvärmeväxlarna för att värme och kyla byggnader. De senaste 10 åren har användningen av så kallade energipålar ökat markant i flera länder som Belgien, Kina, Japan, Schweiz, Nederländerna, Storbritannien och USA. I Sverige har dock intresset varit förvånansvärt lågt trots att pålning är vanligt förekommande i anslutning till svenska byggnader och infrastruktur.

Tidiga uppskattningar antyder att cirka 75 % av värmebehovet och 90 % av kylbehovet i en typisk svensk kontorsbyggnad kan täckas med hjälp av energipålar. De visar också på korta återbetalningstider och stora minskningar av CO_2-utsläpp. Då flera svenska städer är grundlagda på lösa jordar med höga grundvattennivåer finns å andra sidan farhågor att den upprepade uppvärmningen och avkylningen av markvolymer som fås med energipålar kan leda till krypningar (deformationer) i marken. Det mesta av den svenska forskningen kring energipålar och upprepad värmning och kylning av markvolymer genomfördes under 1980-talet. Idag har både analys- och testmetoder som kan ge kunskap om hur marken beter sig blivit mycket bättre. Därför finns det anledning att återuppta ämnet för att få en ökad förståelse för hur den svenska leran uppför sig vid upprepad uppvärmning och nedkylning.

Det här projektet, som finansierats av Energimyndigheten, har omfattat utveckling av modeller för värmeteknisk simulering av energipålar i svenska leror. De nya modellerna innehåller en metod att bestämma den värmetekniska inverkan från byggnaden på energipålarna liksom en beräkning av energipålarnas värmemotstånd. En befintlig borrhålsmodell har också uppdaterats för oregelbundna konfigurationer av energipålar. Modellerna som utvecklats i projektet kan implementeras i befintliga byggnadssimuleringsprogram. Modellerna kan också användas för att utveckla styrsystem och styrsekvenser för att maximera den värmetekniska funktionen hos energipålar som markvärmeväxlare.

Projektet har också demonstrerat användningen av stålpålar och förspända pålar som markvärmeväxlare i svenska mjuka leror och bekräftat vikten av in-situ-mätningar för att kunna bestämma nyckeltal för dimensionering. Resultaten från projektet har presenterats i sju vetenskapliga artiklar och konferensbidrag, tre forskningsrapporter och i ett kapitel i en bok.

Nyckelord: geotermiska pålar, markvärme(källa), energipåle, utformning, modellering, simulering, testning, termiskt motstånd (i en energipåle), uppvärmning, (komfort) kylning, termisk responstest

Foreword

This is the final report of the project titled "Development of Modelling and Simulation Tools for Geothermal Basements and Deep Foundations in Soft Clays" carried out between July 2013 and December 2016 at Division of Building Services Engineering, Chalmers University of Technology.

This work has been funded by the Swedish Energy Agency. It has also been supported by in-kind contributions from many industrial and research partners including NCC Construction, Carrier, Wilo, Grundfos, HP-Borrningar, Oklahoma State University, Lund University, Norwegian University of Science and Technology, Balfour Beatty Ground Engineering, Danfoss, Nibe, Skanska, SP, and Uponor.

We thank all participating companies and research partners for their generous support and enthusiasm throughout this project.

Gothenburg
December 2016
Saqib Javed

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1 Introduction

In the last two decades, ground source heating and cooling systems have emerged as an attractive alternative to conventional heating and cooling systems [1]. Today, the worldwide thermal energy use of ground source heating and cooling systems has exceeded 91,000 GWh. The installed capacities of ground source heating and cooling systems have increased from under 2,000 MWth in 1995 to over 50,000 MWth in 2015 [2]. In Sweden, the thermal energy use of ground source heating and cooling systems is third highest in the world after China and USA. Sweden also has world's third largest installed capacity of ground source heating and cooling systems. There are approximately 400,000 ground source systems installed in single family houses in Sweden. In addition to these small residential systems, there are approximately 600 large ground source heating and cooling systems installed in commercial and office buildings [3].

In Sweden, the most common application of ground source heating and cooling systems is with vertical ground heat exchangers. Over 75 % of Swedish residential ground systems have vertical boreholes as ground heat exchangers. Similarly, two-thirds of the ground source systems installed at Swedish commercial and office buildings have vertical boreholes as ground heat exchangers [3]. The attraction of borehole heat exchangers is that, below a few meters depth, the ground temperature is nearly constant and is not affected by daily or seasonal weather changes. This enables ground to be used as a heat source or a heat sink. Alternatively, the ground can also be used for seasonal storage of heat by loading it at a time of energy surplus and extracting from it at a time of energy deficit [4].

Geothermal piles are rapidly emerging as an effective alternative to borehole heat exchangers [5]. The primary function of pile foundations is to transmit structural load through unstable soil layers to lower ground levels with adequate bearing capacity. However, lately, the use of pile foundations as thermos-active elements is becoming increasingly popular. Geothermal piles share many similarities with traditional vertical borehole heat exchangers, but one key difference between the two technologies is that the geothermal pile systems are almost always used and designed with relatively balanced heating and cooling loads.

Nowadays, many office and commercial buildings in Sweden have both heating and cooling loads [6]. For such buildings, geothermal piles offer a sustainable and cost-effective way of meeting buildings' heating and cooling demands. Initial calculations of potential energy savings indicate that for a typical Swedish office building, geothermal piles can account for around 75 % of heating requirements and 90 % of cooling requirements, thus offering an attractive alternative to traditional borehole heat exchanger systems.

In 2012, a new project was initiated at Chalmers University of Technology to investigate the potential of geothermal piles in Sweden. The project was designed as a multidisciplinary, collaborative, research project bringing together experts in the field of structural engineering, geotechnical engineering, energy installation, building physics, heat pump manufacturing, and piling and energy borehole contracting. Due to its scale and complexity, the project was divided into three smaller projects. Funding for these smaller projects was secured through Swedish Energy Agency (Energimyndigheten), Development fund of the Swedish Construction Federation (SBUF) and Swedish Research Council (Formas), respectively.

This report concerns the project funded by Swedish Energy Agency, Energimyndigheten. The project broadly dealt with the application of geothermal piles to commercial and office buildings in Swedish soft clay conditions. The geological conditions in Sweden are quite different from countries where geothermal piles have been used so far. Hence, there have been concerns among practitioners that application of geothermal piles with cyclic heating and cooling might trigger unwanted deformations in Swedish soft clays. The overall aim of this project was to develop mathematical models and simulation tools for thermal modelling of geothermal piles in Swedish soft clay conditions and to validate the developed models using laboratory and field measurements.

1.1 Background

The thermal behaviour of soils has been investigated by several researchers, for example [7] and [8]. However, most research has been focused on high temperature and compacted clays, and there is a distinct shortage of work on soft compressible clays.

Most of the Swedish research on geothermal piles dates back to 1980s. The Swedish research from that time was focused on the heating of soft clays to high-temperature levels (40-80 °C). The research carried out on the Swedish soft clays, e.g. [9-12], primarily looked at the use of clay for energy storage applications and the implications of geotechnical parameters on the sizing of energy storage systems. However, the topic of cyclic heating and cooling between temperature levels of 3-20 °C, which is most relevant for the application of geothermal piles in soft clays, has not been adequately addressed in the previous research. Today, as a result of technical progress and research, testing methods and theoretical understanding of soft clay behaviour both have improved significantly since the 1990s. Hence, there is a need to revisit the topic of cyclic heating and cooling of Swedish soft clays to fully understand the implications of using geothermal piles.

In order to ascertain the efficacy and safety of geothermal energy structures in Swedish soft clays, a large research project was designed at Chalmers University in the year 2012. The premises of the research project were to study of thermal behaviour of the Swedish soft clays, to investigate the soil-pile interactions, and to explore the applicability of geothermal piles in Swedish soft clays. One of the first steps was to develop and validate mathematical models and tools which could model cyclic heating and cooling in geothermal piles in soft clays for Swedish conditions. This project has dealt with the development of mathematical models for thermal modelling of geothermal piles in Swedish soft clay conditions.

Various past and on-going research activities at the divisions of Building Services Engineering, Building Physics, and Geology provided a solid foundation for this project. The project was supported by the following projects conducted at these divisions.

- Optimization of ground-storage heat pump systems for space conditioning of buildings *(Swedish Energy Agency),*

- Suitable design and control strategies for high-temperature cooling of Swedish office buildings using direct ground systems *(Swedish Energy Agency),*

- Deep Green Cooling *(Swedish Governmental Agency for Innovation Systems, Vinnova),*

- Geothermal foundations in soft clays *(Swedish Research Council, Formas),*

- Thermal piles in soft sensitive clays *(Development Fund of the Swedish Construction Industry, SBUF),*

- Comparative experimental investigation of performance and efficiency of ground collectors for vertical borehole applications *(Swedish Energy Agency).*

1.2 Project Aims and Objectives

The primary objective of this project was to develop modelling and simulation tools for geothermal piles with special emphasis on cyclic heating and cooling loads. The ultimate aim was to facilitate sustainable development of geothermal piles in Swedish soft soil conditions.

The specific goals of the project were as follows.

- Development and validation of modelling and simulation tools for designing and optimizing geothermal pile systems in soft clays.

- Development of a prototype geothermal pile and its testing under heating and cooling cycles.

- Full-scale field testing of instrumented pile heat exchangers to gain confidence for future large-scale exploitation of geothermal piles.

1.3 Research Group and Project Participants

This report presents the results of the project: *Development of modelling and simulation tools for geothermal basements and deep foundations in soft clays*. The project was carried out in a close collaboration between a research group at the Chalmers University of Technology, thirteen private companies, and three international universities. Several other national and international stakeholders also contributed significantly to the project.

Project Research Group

The main research group at Chalmers was based in the division of Building Service Engineering, department of Civil and Environmental Engineering. The group also included representation from the division of Building Technology from the same department. The research group consisted of the following people.

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Research Group Expertise

The project group at Chalmers has strong expertise in the research area. The division of Building Services Engineering has significant research capabilities in design, operation, and control of building heating and cooling systems. The division of Building Technology has extensive research expertise in energy modelling and thermal analysis of building structures and ground. This research project also had direct links to other projects at the division of Building Services Engineering including "Optimization of Ground-Source Heat Pump Systems for Space Conditioning of Buildings" [1, 4, 13, 14] and "Comparative Experimental Investigation of Performance and Efficiency of Ground Collectors for Vertical Borehole Applications" [15].

- Dr. Saqib Javed has worked on thermal energy storage and ground-source heat pump systems for more than 10 years. He is a leading researcher and educator in the field of geothermal energy and has published and presented extensively. He initiated this project and led it through to the conclusion.

- Professor Johan Claesson is an internationally renowned and pioneering researcher in the field of GSHP systems. He is the mathematical brain behind much of Sweden's groundbreaking research on ground heat transfer. He has developed and validated numerous modelling and simulation methods for ground heating and cooling systems.

- Håkan Larsson is an experienced lab engineer with several years of hands-on involvement in heat pumps, borehole heat exchangers, and heating and cooling systems. He has been involved in a number of research and development projects.

Project Research Partners and Sponsors

The project was generously supported by the following sponsors and research partners from industry and academia.

Companies

- Balfour Beatty Ground Engineering, Basingstoke, HAMPSHIRE, RG23 8BG
- Carrier AB, Box 8946, 402 73 GÖTEBORG
- Danfoss Värmepumpar AB, Box 950, 671 29 ARVIKA
- Geotec, Box 1127, SE-221 04 LUND
- Grundfos AB, Box 333, 431 24 MÖLNDAL
- HP-Borrningar AB, Ravingatan 16, 264 39 KLIPPAN
- IFLA HB, Brännabbenvägen 80, 44896 TOLLERED
- NCC Construction Sverige AB, NCC Teknik, 405 14 GÖTEBORG
- Nibe AB, Box 14, 285 21 MARKARYD
- Skanska Commercial Development, Warfvinges väg 25, 112 74 STOCKHOLM
- SP, Box 857, SE-501 15 BORÅS
- Uponor AB, Box 101, 730 61, VIRSBO
- Wilo AB, Box 3024, 350 33 VÄXJÖ

Universities

- Lund University, Mathematical Physics, Box 118, 221 00 LUND, Sweden.
- Norwegian University of Science and Technology, Department of Geology and Mineral Resources Engineering, NO-7491 TRONDHEIM, Norway.
- Oklahoma State University, Building and Environmental Thermal Systems Research Group, OK 74078 STILLWATER, USA.

Research Sponsors

- Energimyndigheten (Swedish Energy Agency), Kungsgatan 43, Box 310, 631 04 ESKILSTUNA.

2 Implementation of the Project

The project was designed and carried out at the Division of Building Services Engineering, Chalmers University of Technology, in close collaboration with over 16 Swedish and international companies, and academic institutions. The research group at Chalmers was responsible for executing the project as well as for achieving the overall project objectives. The industrial and academic partners were actively involved in the project and provided valuable inputs, guidance, and support throughout the project life-cycle. In addition to sharing their knowledge and practical experiences, the industrial and academic partners also contributed to the project in kind by contributing their time, granting access to their research facilities and resources, providing materials and equipment, and sharing invaluable measurement data from field and test measurements.

In order to achieve its objectives, the project was divided into five smaller but logical phases. These phases were not separate isolated series of activities but were overlapping, interrelated and interacting. The following sections discuss the work plan for different phases of the project in more detail.

2.1 Compilation of Existing Knowledge and Practices

A comprehensive overview of the literature and state-of-the-art practices used in industry was designed as the first phase of the project. The literature review was planned to be carried out using leading academic search engines (e.g. Science Direct, Compendex, Scopus, and Google Scholar etc.). The state-of-the-art practices within the industry were aimed to be identified by consulting stakeholders and asking them for their feedback in various formal and informal ways. The stakeholders identified as relevant to the project included (but were not limited to) property developers, contracting companies, pile manufacturers and installers, consultants and designers, and academic and industry researchers.

2.2 Critical Analysis of Existing Knowledge and Practices

The critical analysis of the existing knowledge and contemporary practices related to design and simulation of pile heat exchangers was planned as the second phase of the project. The objective of this phase was to focus on strengths and weaknesses of the existing practices and to identify areas requiring improvements. The results of the analysis were to help determine the required course of actions for developing mathematical models and computational tools required for modelling and simulation of pile heat exchangers.

2.3 Experimental Measurements

Experimental and in-situ testing was identified as the third phase of the project. The experimental studies were planned to be carried out at two to three different in-situ test locations. The experiments were to be used for studying the thermo-mechanical behaviour of pile heat exchangers in Swedish soft clays under controlled laboratory conditions. The experimental data and results were also to be used for developing design and analysis methods for pile heat exchangers.

2.4 Development of Modelling and Design Tools

Development of new modelling tools for design and simulation of pile heat exchangers was planned as the fourth phase of the project. The following mathematical modelling and design tools were planned to be developed in this phase of the project:

- A tool to analyse the effect of heat leakage from the building on underlying pile heat exchangers,
- An analytical method to predict long-term response of pile heat exchangers for any given pile arrangement,
- A method to accurately calculate thermal resistance of pile heat exchangers with single or multiple U-tube pipes.

The project was also aimed at generating new knowledge on thermal response testing and evaluation of pile heat exchangers. Issues like test duration, suitable evaluation methods, test errors, and sensitivities of test results were planned to be addressed comprehensively in this phase of the project.

2.5 Dissemination of Results

Reporting and dissemination of results were regarded as the fifth and final phase of the project. It was planned that results from this research project would be presented at various forums, including:

- Meetings with stakeholders,
- National and international workshops and seminars,
- Research and thesis reports,
- International conference proceedings, for example:
    - ✓ American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) conference,
    - ✓ International Ground Source Heat Pump Association (IGSHPA) Conference,
    - ✓ Federation of European Heating, Ventilation and Air Conditioning (REHVA) Conference.
- Internationally accredited journals, for example:
    - ✓ Applied Energy,
    - ✓ International Journal of Heat and Mass Transfer,
    - ✓ Renewable and Sustainable Energy Reviews.

3 Experimental Setups and Test Conditions

Within the framework of the project, in-situ testing was carried out at 3 different test locations. The experimental testing was performed on steel and precast driven piles, which are used extensively in Sweden. The focus of the in-situ experimental testing was, among others, on the estimation of pile thermal resistance, short- and long-term thermal response of the pile heat exchanger, and the effects of cyclic heating and cooling on soil properties. The following sections provide further details of the experimental testing.

3.1 Steel Pile Heat Exchanger at Chalmers

In this research project, a series of experimental tests were conducted at the full-scale test facility of the division of Building Services Engineering, Chalmers University of Technology [16]. An integral part of Chalmers test facility is its ground source heat pump system, which consists of nine 80-m-deep boreholes, three heat pumps, two dry coolers and a number of thermal storage tanks.

Within the scope of this and other ongoing projects at the division of Building Services Engineering, several new features were added to extend the functionality of the ground source heat pump facility. These included an 18-m-deep steel pile heat exchanger, a mobile thermal response test (TRT) rig, and a distributed temperature sensing system. Figure 3.1a shows the pile heat exchanger with fibre optics installed both inside and outside the steel pile. Figure 3.1b shows an image of the thermal response test being carried out on the pile heat exchanger using the mobile thermal response test rig.

For this project, long-duration thermal response tests were carried out on the steel pile heat exchanger installed in the soft Gothenburg clay. The tests were performed in both heat injection and heat extraction modes. The primary objective of the tests was to study the thermal response of the steel pile heat exchanger under typical Swedish conditions. Another objective was to analyse the thermal resistance of the steel pile heat exchanger.

(a) (b)

Figure 3.1 Chalmers testing facility: (a) Driven steel pile heat exchanger (b) Thermal response test being performed on the driven steel pile heat exchanger.

3.2 Precast Pile Heat Exchangers at HP-Borrningar Test Site

In this project, in-situ testing was also conducted on three driven concrete pile heat exchangers in Helsingborg. The pile heat exchangers were designed and manufactured by Peab Grundläggning AB. They were installed at the Solaris Lab facility belonging to the well-drilling company HP-Borrningar i Klippan AB.

Photo Courtesy: Simon Carlsson

All three precast pile heat exchangers were identical in design. They were all 10 m deep and each pile had a square cross section of 270 mm on each side. A cylindrical hole in the centre of the concrete pile allowed for the insertion of the heat exchanger pipes. The opening was later filled with cement grout. Figure 3.2a shows the three concrete piles with heat exchanger pipes.

In the framework of the project, thermal response tests were performed on the driven precast pile heat exchangers installed in Helsingborg. As with borehole heat exchangers, thermal response tests are also carried out on pile heat exchangers for in-situ determination of design parameters, including ground thermal conductivity and pile thermal resistance. However, in reality, it is often not realized that pile ground heat exchangers are considerably different from borehole heat exchanger. Hence, thermal response tests performed on pile heat exchangers cannot be evaluated using evaluation methods and test protocols of borehole heat exchangers. The main aim of the in-situ tests performed on driven precast was to experimentally study the uncertainties involved in the thermal response testing of concrete pile heat exchangers. The scope of the thermal response tests conducted on concrete pile heat exchangers was limited to heat injection only. Figure 3.2b shows an image of a thermal response test being carried out on a pile heat exchanger using HP-Borrningar's mobile rig.

(a) (b)

Figure 3.2 HP-Borrningar testing facility: (a) Driven precast pile heat exchangers (b) Thermal response test being performed on a driven concrete pile heat exchanger.

3.3 Steel and Precast Pile Heat Exchangers at NCC Recycling Facility

NCC Construction was a key participant in the project. A number of approximately 29-m-deep pile heat exchangers were installed and tested at a NCC site in Utby, Gothenburg. The piles were all driven type and included two steel and two precast concrete piles. The concrete piles were designed and manufactured by Hercules Grundläggning, a member company of NCC group.

The main difference between the piles installed at Utby and at other locations studied in this research project was the mechanical loading of the pile heat exchangers. As can be seen from Figure 3.3a, the pile heat exchangers at Utby were subjected to axial mechanical loading. The combination of mechanical and cyclic thermal loading could potentially trigger undesired settlements and deformation in soft clays.

The main objective of the tests conducted at Utby pile heat exchangers was to comprehensively analyse the thermo-mechanical soil-structure interactions. Hence, the pile heat exchangers were extensively instrumented. The instrumentation was intended to monitor strains, temperatures and pore pressure response along and around the pile heat exchangers. Each pile heat exchanger had observation holes at radial distances of 0.5, 1.5, 3.5 and 5.5 m, respectively. Temperature measurements were taken inside the heat exchanger pipes, and at both sides of the pile heat exchanger boundary using distributed temperature sensing technology. Additional temperature sensors were installed together with piezometers in each of the observation hole at 7, 14, 21 and 28 m depth. Strain measurements were taken inside the pile heat exchangers.

Several tests extended over several weeks were conducted on Utby pile heat exchangers. The tests were performed using cycling heating and cooling. The execution and evaluation of these tests were partly carried out in parallel projects funded by the Swedish Construction Federation, SBUF, and the Swedish Research Council, Formas.

(a)

(b)

Figure 3.3 NCC recycling facility: (a) Driven pile heat exchangers with mechanical loading (b) Mechanically loaded and fully instrumented steel pile exchanger with observation holes.

4 Project Results and Dissemination

The project studied the feasibility of geothermal piles in Swedish soft clays by means of a combination of mathematical modelling and field experimental studies. The project has yielded several important results. New knowledge has been created and mathematical tools for modelling and simulation of geothermal piles have been developed. Detailed results from this project have been presented in a number of journal articles, conference papers, and research reports published within the framework of this project. In the following, a summary of the most significant results, emanating from research which was either fully or partially supported by this project, is presented.

4.1 Compilation of Existing Knowledge and Practices

The project started with an extensive review of literature exploring existing knowledge, mathematical models and best practices related to the pile heat exchangers. A state-of-the-art survey of design and analysis methods for energy geo-structures including borehole and pile heat exchangers was carried out. Most significant results of the literature survey were presented in a state-of-the-art publication [5]. The review article, co-authored with four leading international experts on geothermal piles, presented in detail methods to analyse ground exchange, and thermo-mechanical soil-structure interactions. It also provided an overview of design guidelines and design considerations including thermal boundary conditions, geometric effects, thermal interactions, and load aggregation, among others. Various methods to calculate thermal resistance of pile heat exchangers were presented in [15] and [17]. The thesis report [17] also included a review of thermal response tests methods used for energy piles. A more comprehensive review of thermal response test methods for geothermal piles is in the pipeline and will be published soon.

4.2 Critical Analysis

In this project, a critical analysis of the most used mathematical models and modelling practices for design and analysis of pile heat exchangers was undertaken to assess their appropriateness for the task. The conclusions from these analyses are summarized here.

Due to the superficial similarity between geothermal piles and borehole heat exchangers, the design and thermal analysis of pile heat exchangers is commonly carried out based on methods developed for borehole heat exchangers, for example [18-21]. This not only introduces several complications in the analysis but also adds significant uncertainties into the results. The pile heat exchangers are different from traditional borehole heat exchangers in several ways. The pile heat exchangers have different boundary conditions and end effects than borehole heat exchangers. They typically also have significantly larger diameters and considerably smaller aspect ratios (length to diameter) than borehole heat exchangers. Moreover, pile heat exchangers generally have unequal lengths and irregular configurations within an installation, which is rather uncommon for borehole heat exchanger installations.

Given, all these differences and limitations, there are, obviously, great difficulties in applying design and analysis methods developed for borehole heat exchangers to pile heat exchangers. There is also conflicting evidence in literature in regards to what extent methods developed for calculating thermal resistance of borehole heat exchangers can be used for pile heat exchangers.

4.3 Experimental Measurements

In the framework of this project, experimental and in-situ measurements were carried out at three different test locations. Details of the experimental setups and test procedures are provided in Chapter 3 of this report. The emphasis of experimental studies was primarily on studying the thermal behaviour of geothermal piles in both heating and cooling modes. Thermal response measurements were taken for both steel and precast piles over short to medium timescales. The in-situ measurements showed that in comparison to borehole heat exchangers, geothermal piles require substantially longer thermal response tests for calculation of design parameters [17], including ground thermal conductivity and pile thermal resistance. The experimental measurements also indicated that thermal response of pile heat exchangers is directly influenced by surface end effects. The in-situ experiments were also used to study thermo-mechanical behaviour and soil-pile interactions under cyclic loads. The results on thermo-mechanical behaviour and soil-pile interactions will soon be published as a licentiate thesis and a journal article.

The project also generated a substantial amount of experimental data for pile heat exchangers. This data will be made available as reference data sets for development and validation of new computational models for geothermal piles and will thus be highly valuable for future research projects.

4.4 Theoretical Analysis and Development of Modelling and Design Tools

Within the scope of this project, various aspects of modelling geothermal piles were investigated in detail. A number of modelling and simulation tools for design and analysis of pile heat exchangers have been developed and validated.

A comprehensive analysis of published methods for calculating thermal resistance indicated that most existing methods suffer from inaccuracies resulting from oversimplified assumptions. New methods have been developed to accurately calculate the pile thermal resistance [22-24]. The methods include explicit second-order multipole formulas for single U-tube pile heat exchangers and explicit first-order multipole formulas for multi-pipe pile heat exchangers. The developed formulas have been shown to be very accurate.

Thermal analysis of geothermal piles suggested that the pile heat exchangers experience a time-dependent temperature field from the building above them, which, over time, develops into a steady-state temperature field. This is because the ground is heated by the excess temperature from the building and its foundation. In this project, a method has been developed to incorporate the effects of the excess temperatures from a building in the design of the pile heat exchangers [25]. The method is quite straightforward and can be easily implemented in any computer code. A frequency domain method [26] to model the heat transfer between the injected and/or extracted heat and the temperature of the fluid exiting a borehole or a pile heat exchanger has also been developed. The method is based on in-situ measurements and focuses particularly on the short-term heat transfer.

4.5 Dissemination of Results

Dissemination of the project results was realized in many different ways. Throughout the project duration, the results were regularly presented in meetings with different project Stakeholders. The results were also presented in scientific journals, international conferences, and other national and international seminars and workshops on a regular basis. The dissemination of results is described in the following in more detail.

4.5.1 International Seminars and Workshops

The project results were disseminated internationally through interactive seminars and workshops with key stakeholders. Following is the list of seminars and workshops attended to disseminate the results from this project through formal and informal channels.

- Turin Meeting and Seminar of the European network for shallow geothermal energy applications in buildings and infrastructure (GABI), December 5-7, 2016, Torino, Italy.

- Cluj Meeting and Seminar of the European network for shallow geothermal energy applications in buildings and infrastructure (GABI), March 21-23, 2016, Cluj, Romania.

- Lisbon Meeting and Seminar of the European network for shallow geothermal energy applications in buildings and infrastructure (GABI), December 10-11, 2015, Lisbon, Portugal.

- Second European Workshop on Renewable Energy Systems (EWRES 2013), September 20-29, 2013, Antalya, Turkey.

- International Workshop on Thermoactive Geotechnical Systems for Near-Surface Geothermal Energy: From Research to Practice, March 25-27, 2013, Lausanne, Switzerland.

4.5.2 Project Publications

Following is a partial list of publications in which the research was fully or partly supported by this project. Please note that this is not a comprehensive list. A few additional publications from the project are still in the pipeline. Some of them are listed under forthcoming category in the following. The additional papers will link the thermal aspects of pile heat exchangers (i.e. the focus of this project) to the geotechnical aspects of geothermal piles (i.e. the focus of two ongoing Chalmers projects funded by SBUF and FORMAS).

Journal Articles:

1. Javed, S., Spitler J, 2017. Accuracy of borehole thermal resistance calculation methods for grouted single U-tube ground heat exchangers. Applied Energy, vol. 187, pp. 790-806. http://dx.doi.org/10.1016/j.apenergy.2016.11.079

2. Bourne-Webb, P., Burlon, S., Javed, S., Kürten, S. and Loveridge, F., 2016. Analysis and design methods for energy geostructures. Renewable and Sustainable Energy Reviews, vol. 65, pp. 402-419. http://dx.doi.org/10.1016/j.rser.2016.06.046

3. Spitler, J., Javed, S. and Ramstad, R., 2016. Natural convection in groundwater-filled boreholes used as ground heat exchangers. Applied Energy, vol. 164, pp. 352-365. http://dx.doi.org/10.1016/j.apenergy.2015.11.041

4. Monteyne, G., Javed, S. and Vandersteen, G., 2014. Heat transfer in a borehole heat exchanger: Frequency domain modeling. International Journal of Heat and Mass Transfer, 69, pp. 129-139. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.10.015

Conference Proceedings:

1. Javed, S. and Claesson, J., 2017 (Accepted). Second-order multipole formulas for thermal resistance of single U-tube borehole heat exchangers. Proceedings of IGSHPA 2017 IGSHPA Technical/Research Conference, Denver, USA.

2. Spitler, J., Grundmann, R. and Javed, S., 2016. Calculation tool for effective borehole thermal resistance. Proceedings of 12th REHVA World Congress (Clima 2016), Aalborg, Denmark.

3. Javed, S., 2013. Thermal Response Testing: Results and Experiences from a Ground Source Heat Pump Test Facility with Multiple Boreholes. Proceedings of 11th REHVA World Congress (Clima 2013), Prague, Czech Republic.

Research Theses and Reports:

1. Claesson, J., 2016. Multipole method to calculate borehole thermal resistances. Additions to background report from June 2012. Mathematical report 2, Preliminary version. (Chalmers University of Technology.) Sweden.

2. Claesson, J., 2016. Energy piles under a heated rectangular building. Required fluid temperature for zero heat load. Mathematical background report, Preliminary version. (Chalmers University of Technology.) Sweden.

3. Carlsson, S., 2015. Energy piles – A Thermal Response Test on a pre-cast concrete energy pile. Engineering Geology, Master's thesis, TVTG – 5142, 50 pages. (Lund University.) Sweden.

Book Chapters:

1. Javed, S. and Spitler, J., 2016. Calculation of borehole thermal resistance. In: Rees S, editor. Advances in ground-source heat pump systems. Woodhead Publishing, pp. 63-95. http://dx.doi.org/10.1016/B978-0-08-100311-4.00003-0.

Popular Science Articles/Presentations:

1. Javed, S., 2016. Geothermal piles – Research updates from Sweden. Meeting COST Action TU1405, European network for shallow geothermal energy applications in buildings and infrastructure, Torino, Italy, 2016-12-06.

2. Javed, S., 2015. Thermal modelling of geothermal piles. Meeting COST Action TU1405, European network for shallow geothermal energy applications in buildings and infrastructure, Lisbon, Portugal, 2015-12-10.

3. Javed, S., 2013. Design and simulation of ground source heating and cooling systems. Invited presentation, Second European Workshop on Renewable Energy Systems (EWRES 2013), Antalya, Turkey, 2013-09-26.

4. Javed, S., 2013. Modelling, simulation, and experimentation of energy pile. International Workshop on Thermoactive Geotechnical Systems for Near-Surface Geothermal Energy: From Research to Practice, Lausanne, Switzerland, 2013-03-25.

Forthcoming Journal Articles:

1. Characterization of ground thermal behaviour for shallow geothermal energy applications.

2. First-order multipole formulas for thermal resistance of multi-pipe ground heat exchangers.

3. Thermal and geotechnical aspects of heating and cooling cycles on steel pile ground heat exchangers.

5 Discussion and Conclusions

Modelling and simulation for design and analysis of ground source heating and cooling systems with geothermal piles is an intricate process. It involves modelling of several sub-systems including building, heat pump, and pile heat exchangers, among others. Of these, modelling of the geothermal piles is of particular interest as the fluid temperature exiting the pile heat exchanger affects the performance and efficiency of the whole system. Also, the knowledge of fluid temperature exiting the geothermal piles is the principal prerequisite for technical, economical and operational optimization of ground source heating and cooling systems. The fluid temperature exiting a geothermal pile system depends, among other things, on thermal behaviour of the pile heat exchangers, the thermal response of the ground surrounding the pile heat exchangers, the thermal interactions between the pile heat exchangers, and the excess temperature from the building above the geothermal piles. In this project, all these factors were studied in detail through mathematical modelling, simulation studies, and in-situ experiments.

5.1 Discussion

Using geothermal pile heat exchangers is a sustainable and cost-effective way of meeting buildings' heating and cooling demands. The primary function of a pile is to transmit structural load through unstable soil layers to lower ground levels with adequate bearing capacity. However, initial calculations of potential energy savings in Sweden indicate that for a typical office building, geothermal piles can provide around 75 % of heating demands and 90 % of cooling demands, thus offering an attractive alternative to traditional heating and cooling systems including borehole systems. The geothermal piles can be used all over the world for buildings with foundation piles. Their application to commercial and office buildings that require both heating and cooling at different times of the year is of particular interest.

As a ground heat exchanger, the function of a geothermal pile is to transfer heat energy between the building and the soil surrounding the pile heat exchanger. The heat transfer is a cyclic process extending over many years [27, 28]. In summer the heat is transferred from the building to the soil through the pile heat exchanger, whereas in winter the heat flows from the soil to the building through the pile heat exchanger. However, currently, there is a scarcity of tools available to accurately model the thermal response of the geothermal piles. Borehole heat exchanger models with many unrealistic simplifications are used instead. Using borehole models place major limitations on design and analysis of pile heat exchangers.

A major limitation of using borehole heat exchanger models for geothermal piles is their lack of capability to apply the surface temperature boundary condition. Ground surface conditions affect the underground temperatures down to about 10 meters below the surface. For borehole systems, the top surface conditions are relatively less important and are mostly ignored. This is because the total depth of a borehole is quite long (often more than 100 m). However, for geothermal piles, which are typically 20-50 m deep, the temperature conditions at the top surface of the pile heat exchangers are quite important and therefore must be considered. This means the temperature field caused by the excess temperature from the building above a geothermal pile arrangement should be incorporated in its modelling.

Another limitation introduced by the use of borehole modelling tools for the design and analysis of geothermal piles is regarding the irregular arrangement of pile heat exchangers. Existing borehole modelling tools cannot be used for irregular arrangements of pile heat exchangers. This is because borehole systems are customarily drilled in regular configurations (line, U-shape, L-shape, rectangular, circular, etc.) to meet the specific heating and cooling demands of the building. On the other hand, the number and arrangement of foundation piles is solely based on structural considerations, and thus pile heat exchangers are often placed in irregular arrangements.

A further limitation of using borehole models for modelling of geothermal piles is in regards to the accuracy of methods for calculating pile thermal resistance. Borehole heat exchangers have a very restricted range of diameters (around 110-150 mm) and hence most boreholes use single U-tube or double U-tube heat exchangers with relatively small distance between U-tube pipes. On the other hand, geothermal piles may have diameters from a few centimetres to many hundred centimetres. They are wide enough to hold several U-tubes and the distance between U-tube pipes can be fairly large. Consequently, calculation of thermal resistance of a geothermal pile, which depends on the pile diameter and the number and placement of U-tube pipes in the pile, is more complex in comparison to the calculation of borehole thermal resistance. Most of the borehole thermal resistance calculation methods [15, 29] are based on several assumptions, and their applicability to pile heat exchangers is limited by many complexities.

This project was broadly aimed at demonstrating the feasibility of geothermal piles in Swedish soft clays. Within the scope of the project, several tasks were undertaken to demonstrate the applicability and utility of foundation piles as pile heat exchangers. These tasks included development and testing of new mathematical models, application of existing modelling and simulation approaches, and analysis and evaluation of in-situ testing. New mathematical models [23, 25] and tools [22, 24] have been specifically developed to address the above-mentioned shortcomings in the modelling of pile heat exchangers. The new models include a method to determine the thermal impact of the building on pile heat exchangers and calculation methods to evaluate the thermal resistance of pile heat exchangers. The method developed to analyse the effect of excess temperature from the building on geothermal piles allows the determination of time-dependent temperature field in the ground using single-integral expressions. Explicit formulas for steady-state conditions have also been developed. The expressions are sufficiently straightforward to be implemented in any computer code. Methods for calculating thermal resistance of pile heat exchangers have been developed for both single and multi U-tube heat exchangers. For geothermal piles with single U-tube heat exchangers, closed-form second-order multipole formulas for the calculation of pile thermal resistance and total internal thermal resistance have been developed. For geothermal piles with multi U-tube heat exchangers, explicit single-order multipole formulas have been developed. The new formulas can be used for all cases where the U-tube shanks are symmetrically placed in the pile heat exchanger. The developed methods for calculating pile thermal resistance provide significant accuracy improvements over existing methods.

The project has also examined the application of existing borehole models for modelling of pile heat exchangers in irregular configurations. It has been found that only a hand full of available methods/programs can adequately model the irregular pile heat exchanger arrangements. The prominent models among these are the Superposition Borehole Model

(SBM) and the finite line source model for multiple ground heat exchangers [1]. SBM can account for thermal interactions between pile heat exchangers in a very exact way. However, the availability of the model is limited to a not so user-friendly FORTRAN implementation. On the contrary, finite line source model for multiple ground heat exchangers is relatively simple to implement and is computationally efficient. Though slightly less accurate than the SBM, the finite line source model for multiple ground heat exchangers [1] has been shown to be a reasonably accurate method for modelling of irregular arrangements of pile heat exchangers.

Another significant research contribution of the project has been in the area of thermal response testing of geothermal piles. As for borehole systems, thermal response tests are also conducted on pilot pile heat exchangers to determine thermal properties when sizing ground source systems with geothermal piles. At present, regulatory guidelines on performing thermal response tests on pile heat exchangers are missing. Hence, tests on geothermal piles are performed and evaluated using methods and protocols originally developed for borehole heat exchangers, for example [30-34]. In this project, it has been demonstrated that in comparison to borehole heat exchangers, thermal response tests carried out on geothermal piles require considerably longer test durations. The project has also dealt with various other uncertainties and ambiguities in the measurements and analyses of driven piles, which are extensively used in Sweden. For example, new correlations have been developed to model natural convection in annulus region of driven steel piles [35].

All of the mathematical methods and tools developed within the project have been tested and validated using simulation, and in-situ experimental studies. Simulations were performed using state-of-the-art research and commercial tools. Experiments were conducted in carefully controlled experimental setups developed within the scope of this project. The methods and tools developed in the framework of this project are capable of accurately simulating the thermal response of geothermal piles. Currently, the methods and the data developed from this project are being used to study thermo-mechanical behaviour and soil-pile interactions of pile heat exchangers in the projects funded by SBUF and FORMAS.

5.2 Conclusions

This project dealt with the feasibility of using ground source heating and cooling in Swedish buildings by means of pile heat exchangers. The main outcome of the project is the development of modelling and simulation methods and tools for geothermal piles in Swedish soft clays. The methods and tools developed in this project can be used for design and analysis of all types of pile heat exchangers. The mathematical models from the project can be implemented in any computer code to be incorporated in the existing building energy simulation software. The models can also be used to develop controllers and control schemes to maximize the performance of the pile heat exchanger systems. The project has also demonstrated the application of driven steel and precast pile heat exchangers in Swedish soft clays and has established the importance of acquiring in-situ measurements to determine key parameters that cannot be rigorously evaluated otherwise. The results from the project have been presented in seven journal and conference proceeding papers, three research reports, and one book chapter.

The major achievements of the project are summarised in the following.

- Development of a mathematical model to determine the thermal impact of the building and its foundation on the ground and pile heat exchangers.

- Development of explicit second-order multipole formulas to calculate thermal resistance of geothermal piles with single U-tube heat exchangers.

- Development of explicit first-order multipole formulas to calculate thermal resistance of geothermal piles with any given number of U-tube heat exchangers.

- Demonstration of applying the finite line-source model for multiple boreholes on geothermal pile arrangements.

- Demonstration of using driven steel and precast piles as ground heat exchangers in Swedish soft clays.

- Exposition of methods for testing and evaluation of in-situ measurements performed on pile heat exchangers.

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